Experimental Observation and CFD Prediction of Flow Mixing in a Rod Bundle with Mixing-vane Spacer Grid

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Abstract The flow visualization experiment and computational fluid dynamics (CFD) analysis were performed to investigate flow mixing in a rod bundle with the mixing-vane spacer grid. The test bundle is a 4x4 square rod bundle with the pitch-to-rod diameter ratio (P/D) of 1.35 which simulates typical fuel assembly for pressurized water reactor. The working fluid is a water with the bundle-average velocity of 1.5 m/sec and the Reynolds number of 33000. The particel image velocimetry (PIV) and laser doppler velocimetry (LDV) systems were used to measure the axial and lateral velocity distributions of turbulent flow in rod bundle using matching index of refraction technique. A CFD approach was also applied to simulate the flow mixing experiment by using a polyhedral meshing technique. The experiment and CFD analysis showed a large swirl and crossflow near the downstream of mixing-vane grid. The lateral velocity caused by the mixing vane was observed to increase up to 67% of the bundle-average flow velocity. The axial RMS velocity was also estimated to be higher than 27% of the bundle-average flow velocity near the mixing-vane grid and rapidly decreased further downstream.
Keywords: Flow mixing, Swirl, Crossflow, Rod bundle, PIV, LDV, CFD

1 Introduction

The nuclear fuel assembly loaded in a pressurized water reactor(PWR) is a rod bundle that is supported by a spacer grid. The commercial PWR fuel assembly is typically a 16x16 or 17x17 square array of fuel rods. The diameter of fuel rod (D) is 9.5-9.8 mm and the ratio of rod pitch and diameter (P/D) is 1.33-1.35. The coolant(water) flows axially through the subchannel formed between the rods. Since the spacer grid affects the coolant flow distribution in the fuel bundle, the spacer geometry has a strong influence on a thermal-hydraulic performance of fuel assembly such as the critical heat flux(CHF) and pressure drop. The mixing-vane spacer designs have been invented and implemented in many of commercial PWR plants to improve the CHF performance by increasing the coolant flow mixing in fuel assembly. Among numerous mixing-vane designs, the split-type vane [1] is widely adopted in many of advanced fuel assembly for PWR. The split-vane grid is configured to promote a crossflow mixing of the coolant through the fuel assembly. A twist-vane grid [2] for the PWR fuel assembly was invented by Korea Atomic Energy Research Institute to enhance a crossflow mixing between adjacent subchannels as well as a swirl mixing within the subchannel. Fig. 1 illustrates the twist-vane grid consisting of triangular vane supports and pairs of polygonal vanes which are integrally formed on the top edges of grid straps.

It is important to understand the detailed structure of a flow mixing and heat transfer downstream of a mixing-vane grid for the safe and reliable operation of nuclear power plant. Hence, there have been many experimental and numerical studies on flow mixing and heat transfer downstream of the mixing-vane grid in rod bundle geometry. References [2] and [3] performed an experiment to examine the flow mixing and turbulent characteristics in a rod bundle with the split-vane spacer grid. References [4] and [5] measured the lateral flow field in typical subchannels of rod bundle with the split-vane grid. There have been also many numerical works to evaluate the rod-bundle flow mixing caused by the split-vane grid [6-8]. References [9, 10] and [11] carried out an experimental study to investigate the effect of split-vane grid on heat transfer for rod bundles. There was an experimental study [13] on forced flow mixing in rod bundle with the twist-vane grid. The axial and lateral velocity were measured downstream of the twist-vane grid for turbulent flow in regular and tight-lattice rod bundles.

The objective of this study is to compare the experimental data and CFD prediction of flow mixing in a 4x4 rod bundle for the pitch-to-diameter ratio of 1.35, i.e., P/D=1.35. Downstream of the twist-vane grid, the axial and lateral velocity were measured to evaluate the flow mixing by using the laser Doppler velocimetry

(LDV) and particle image velocimetry (PIV) systems. The mean and root-mean-square (RMS) velocities were obtained from the measurements of instantaneous velocity. A CFD analysis was also performed to simulate the flow mixing experiment and compare the prediction of velocity distributions with the experimental result.

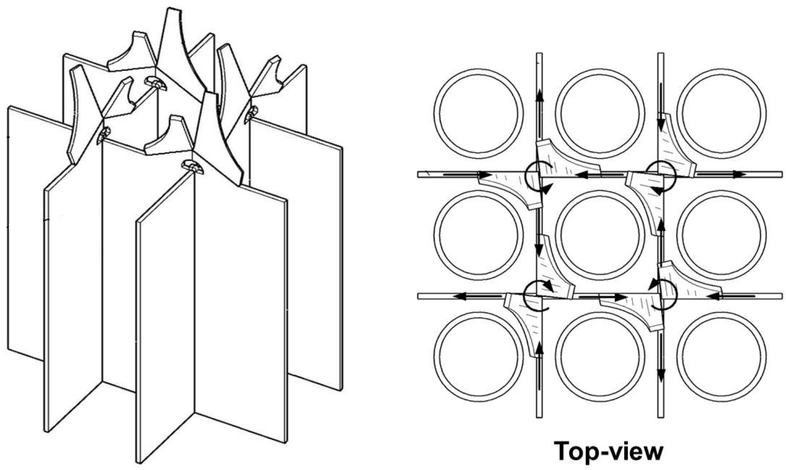

Fig. 1 Schematic of twist-vane grid for PWR fuel assembly (Patent EP1139348, [2])

2 Experimental method

An Omni flow experimental loop (OFEL) has been built to measure the flow mixing characteristics in rod bundle simulating the PWR fuel bundle. The OFEL in Fig. 2 consists of a test section, a water pump, s storage tank and a flow meter. The test section is a 4x4 square rod bundle with the twist-vane grid and rod supporters which is installed in a square flow housing. Figure 3 shows the test section, test rod bundle and twist-vane grid. The test bundle uses a cylindrical rod in acetal resin with the diameter (D) of 25.4 mm and the length of 2000 mm. It should be noted that the fluorinated ethylene propylene (FEP) tubes are used to match the refractive index of water. The FEP tubes (200 mm in length) are filled with water and placed downstream of the twist-vane grid. The central subchannel is a target flow channel for measuring the flow distributions in detail. The twist-vane grid was manufactured by a 3-D printing technology using acrylonitrile butadiene styrene (ABS). The vane angle is 35 degree from main flow direction.

The water flow rate is controlled by the VFD (Variable Frequency Drive) and measured using mass and turbine flow meters. To measure the water temperature, a T-type thermocouple was used. All experimental data are collected using a data acquisition system (Agilent, 34970A). The working fluid is pure water at 35 ^{o}C and the pressure in the test section is approximately 1 bar.

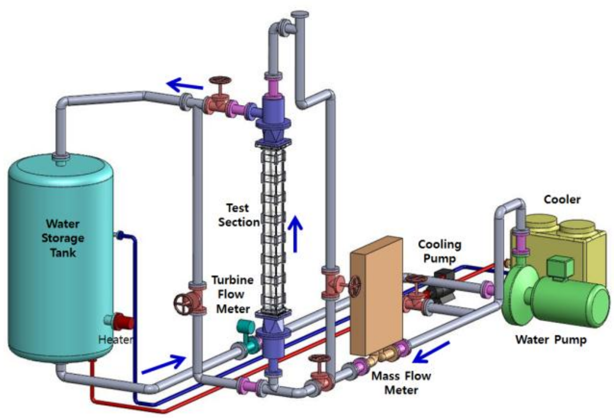

Fig. 2 Schematic of the test loop for rod-bundle flow

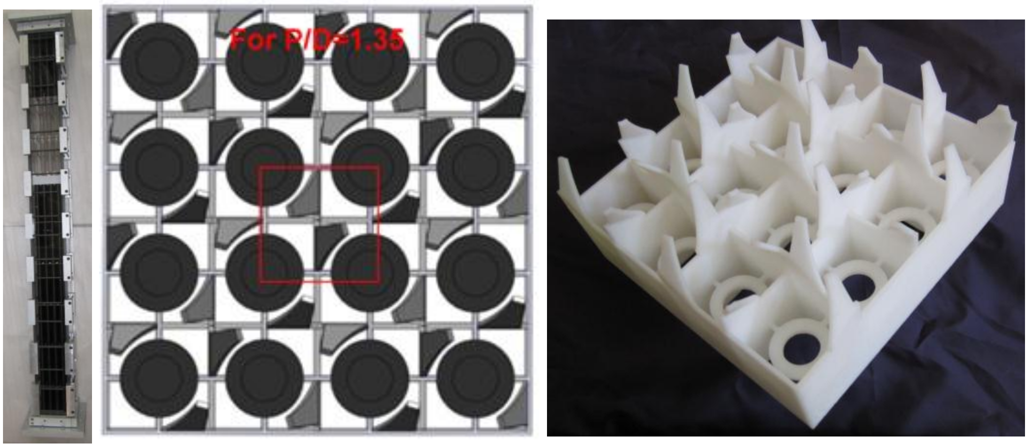

Fig. 3 Test section, rod bundle and twist-vane grid

A time-resolved PIV system was installed to measure the flow structure in a rod bundle using the Matching Index of Refraction (MIR) technique [14]. The laser system has a dual power of 20 mJ with a pulse rate of 1 kHz and a wavelength of 527 nm. The high speed camera used is a Speed Sense 9072 with 2190 fps at 1280x800 pixels. A mini-LDV system (130 mW, 660 nm) was also installed to measure the local flow structure in a rod bundle. The PIV system was used to measure the lateral velocity distribution in the central subchannel downstream of the mixing-vane grid. The mini-LDV system was used to measure the axial velocity distribution in the main flow direction at the centers of the subchannel and the rod-to-rod gap.

The fully developed flow condition in the 4x4 rod bundle geometry is anticipated upstream of the twist-vane grid in this experiment. To check the uniformity of the inlet flow, using the LDV technique, the axial velocity and its RMS (Root-Mean-Square) velocity (i.e., standard deviation) around the center of the subchannels are measured at -20D (i.e., -508 mm, where minus sign means upstream of the spacer grid). The bundle-average flow velocity is 1.5 m/sec and the Reynolds number is 33000.

Downstream of the twist-vane grid, the mean lateral velocity and its RMS velocity in a center subchannel were measured at 1.5D, 3D, 6D, 10D, 14D, 20D downstream of the spacer grid by using the PIV technique. In addition, at the centers of a subchannel and a rod-to-rod gap, the measurements of axial velocity and its RMS velocity are carried out in the range of 40 mm to 200 mm along the axial direction, using the LDV technique.

Numerous PIV images were taken to obtain the average velocity field by adaptive correlation and averaging process. Figure 4 illustrates the instantaneous and average lateral velocity field in the central subchannel taken by the PIV system. The average image was generated by a vector averaging technique using 6000 instantaneous images. The LDV data was acquired with average rate of minimum 8 kHz to measure the mean and RMS velocity from approximately 100000 samples.

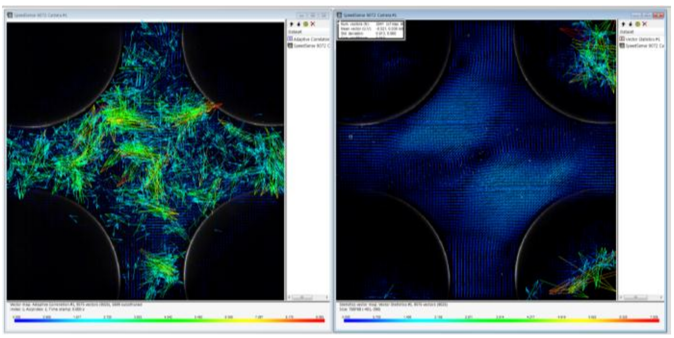

Fig. 4 PIV images for instantaneous and average velocity vector in the central subchannel

3 Numerical method

A CFD analysis was performed to simulate the bundle-mixing experiment by using a commercial CFD code, STAR-CCM+ v.8.04 [15]. Figure 5 shows the CFD model of test bundle and mesh generated by using polyhedral meshing technique. The CFD model represents the 4x4 rod bundle of 4000 mm in length including a single twist-vane grid at the center. There are five prism layers on rod surface in order to more accurately model the boundary layer. Total number of mesh is approximately 14.7 million cells.

A uniform flow was assumed at the inlet boundary far upstream of the spacer grid. A constant pressure was applied at the outlet boundary far downstream. Isothermal and no-slip condition were also applied at the rod surface and housing wall. The working fluid is water at the experimental conditions. Since the overall Reynolds number for the test condition is 33000, the SST k-ω model [16] was used to simulate flow turbulence. The SST model has been known to predict the swirling turbulent flow well with the excellence in convergence.

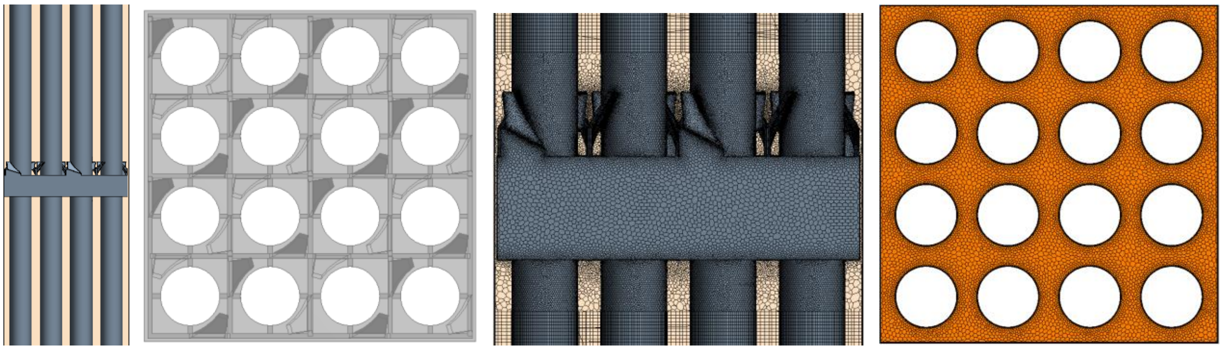

Fig. 5 CFD model and mesh for the 4x4 rod bundle

4 Results and discussions

The PIV measurement shows flow mixing caused by the twist-vane grid as illustrated in Fig. 6. Near downstream of the twist-vane grid at 36 mm (1.4D), it shows a large elliptic swirl in the central region and crossflow in the gap region. It is also noted that a secondary swirl is generated in the peripheral region near the gap. Further downstream of the twist-vane grid at 152 mm (6D), a single circular swirl is shown in the central region and asymmetric crossflow in the gap region. The CFD simulation also predicted the flow mixing pattern such as swirl and crossflow similar to the PIV measurement as shown in Fig. 7.

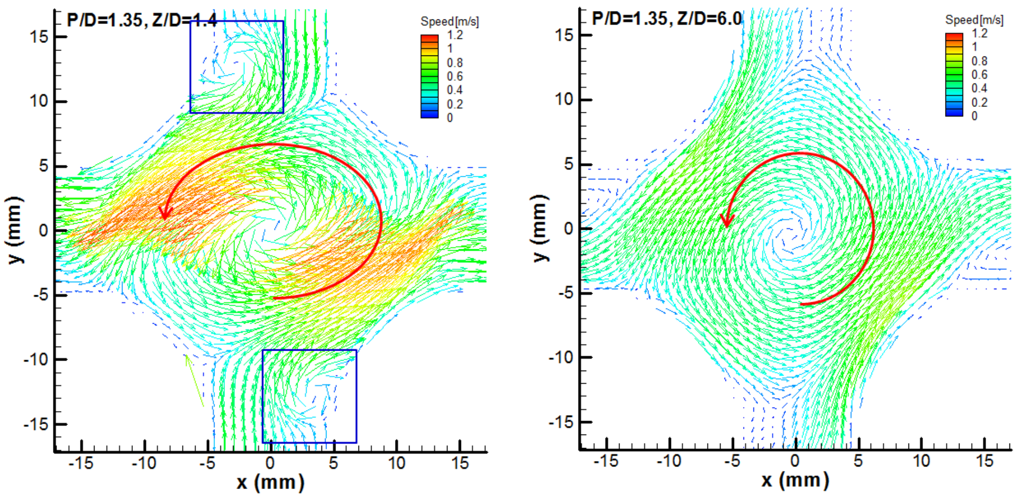

Fig. 6 PIV measurement of flow mixing in the center subchannel of 4x4 rod bundle: (left) Z=36 mm (1.4D), (right) Z=152 mm (6D)

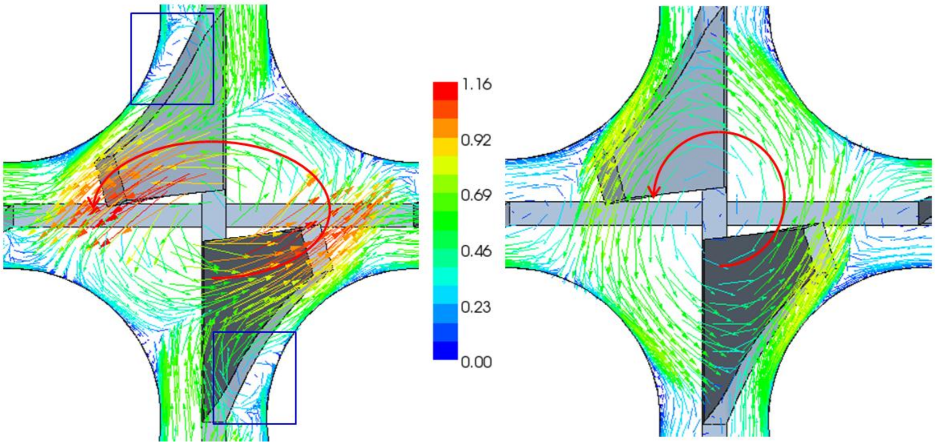

Fig. 7 CFD prediction of flow mixing in the center subchannel of 4x4 rod bundle: (left) Z=36 mm, (right) Z=152 mm

Figure 8 compares the experimental and CFD distributions of lateral velocity downstream of the twist-vane grid. The vertical velocity (V) along the horizontal centerline of the subchannel increased up to approximately 1.0 m/sec (67% of bundle-average velocity) near the downstream of vane grid, i.e., Z=36. The vertical velocity decreased to 10% of bundle-average velocity far downstream, i.e., Z=508 as the swirl decays away from the vane grid. The CFD prediction of vertical velocity agrees with the experimental result well and shows a symmetric distribution around the subchannel center, i.e., X=0. The crossflow velocity (U) along the gap centerline shows the asymmetric distribution around the gap center (Y=0) with the maximum velocity of 0.6 m/sec (40% of bundle-average velocity). The CFD prediction of crossflow velocity agrees well with the experimental result near downstream (Z=36) and shows somewhat large difference with the measured one further downstream (Z=152 & 508). However, it is also noted that the CFD profiles of crossflow velocity reasonably agrees with the experimental profiles. The crossflow velocity also decreased to lower than 0.15 m/sec far downstream.

The streamwise distribution of axial velocity (W) is compared in Fig. 9 for the subchannel and gap centers. The axial velocity at the subchannel center decreased near downstream of vane grid (Z < 50) and increased to an asymptotic value further downstream. The CFD calculation shows an excellent agreement with the measured axial velocity at the subchannel center. The axial velocity at the gap center shows a saddle-type distribution around 50 mm downstream of vane grid and decreased to an asymptotic value further downstream, i.e., Z > 100. The CFD calculation also shows the variation of axial velocity at the gap center which is similar to the experimental result. However, the experiment and CFD prediction shows a large difference of axial velocity at the gap center in magnitude approximately 150 mm downstream of vane grid.

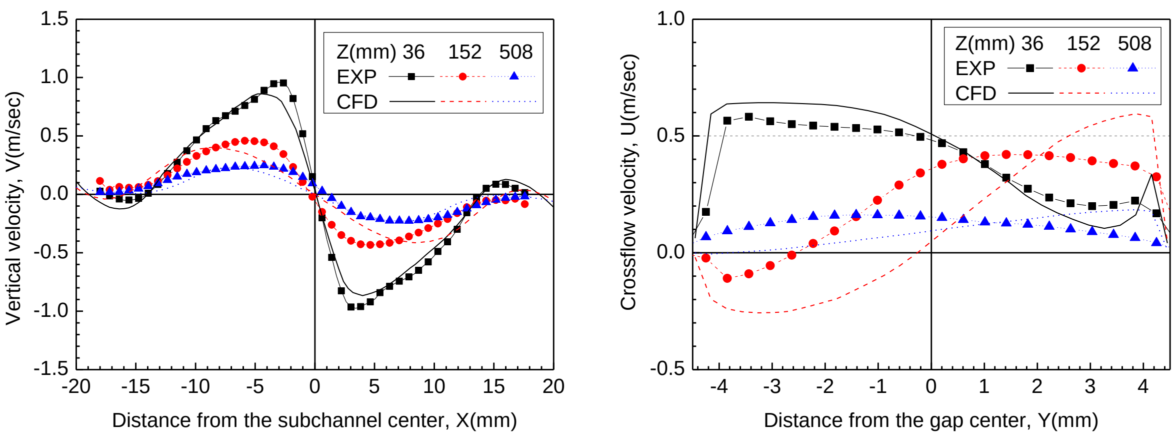

Fig. 8 Comparisons of experimental and CFD lateral velocity downstream of the twist-vane grid: (left) vertical velocity along the horizontal centerline, (right) crossflow velocity along the gap centerline

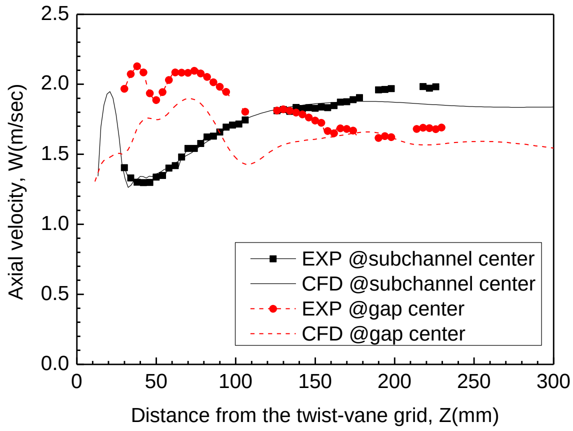

Fig. 9 Comparison of experimental and CFD axial velocity downstream of the twist-vane grid

5 Conclusions

An experimental and CFD analysis were performed to investigate flow mixing in a rod bundle caused by the mixing-vane spacer grid. The PIV and LDV systems were applied to measure axial and lateral velocity in a 4x4 rod bundle with the twist-vane grid. A CFD approach was also used to simulate the flow mixing experiment in rod bundle. Both the experiment and CFD simulation showed a flow mixing pattern with swirl in the central region and crossflow in the gap region. The vertical velocity in the central region of the subchannel increased to approximately 67% of bundle-average flow velocity (1.5 m/sec) and the crossflow velocity in the gap region increased to 40%. The CFD prediction showed a good agreement with the experimental result of vertical velocity along the centerline of the subchannel but somewhat large difference with the measured crossflow velocity. The axial velocity at the subchannel center decreased near downstream of vane grid and increased to an asymptotic value further downstream. The axial velocity at the gap center shows a saddle-type distribution around 50 mm downstream of vane grid and decreased to an asymptotic value further downstream. The CFD calculation showed an excellent agreement with the measured axial velocity at the subchannel center and the variation of axial velocity at the gap center similar to the experimental result.

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